Impacts of Ionospheric Outflow on Simulations of the Magnetosphere

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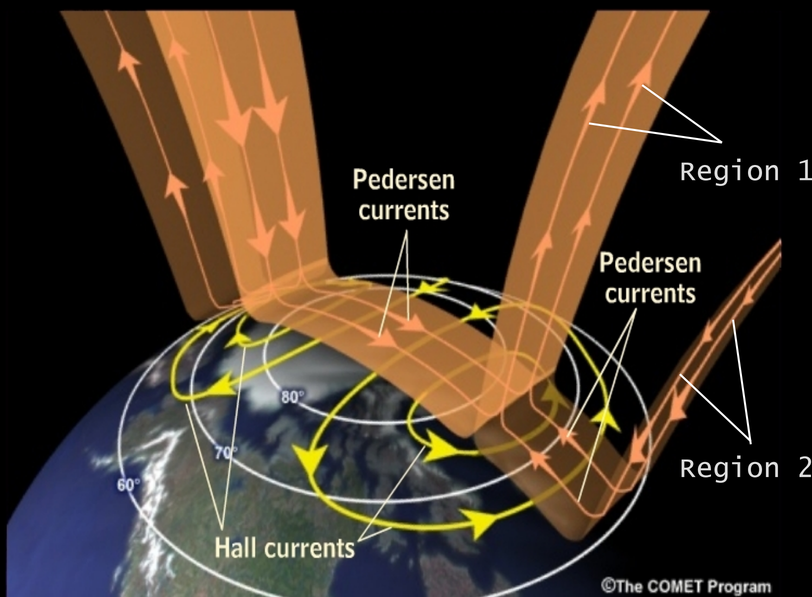
Outline

- Motivation & Background
- Ion Outflow Methods
  - Winglee – Fixed Lower BC
  - SWMF – POWM & Fixed Lower BC
  - MFLFM – Empirically Driven & Fixed Lower BC
- Impacts
  - CPCP
  - Magnetotail Dynamics
  - Impacts on Ring Current
- Conclusions

Motivation

- Ever since the detection of O+ in the magnetosphere by *Shelly et al.* (1972) it has been known that the ionosphere was a source of magnetospheric plasma
- Using Cluster observations *Kistler et al.* (2005) *and Kistler et al.* (2010) showed that O^+ can become the main component of the plasma sheet during strong magnetic storms with the cusp as a likely source region
- *Shay and Swisdak* (2004) found that the rate of reconnection is controlled by the heavy ion species in multi-species simulations
- The early work of creating magnetospheric general circulation models (GCM) concentrated on the electrodynamic coupling between the magnetosphere and ionosphere
- With the advent of the multi-fluid version of the these GCMs it is now possible to consider the effect of ionospheric H^+ and O^+ on magnetospheric dynamics

Electrodynamic Coupling

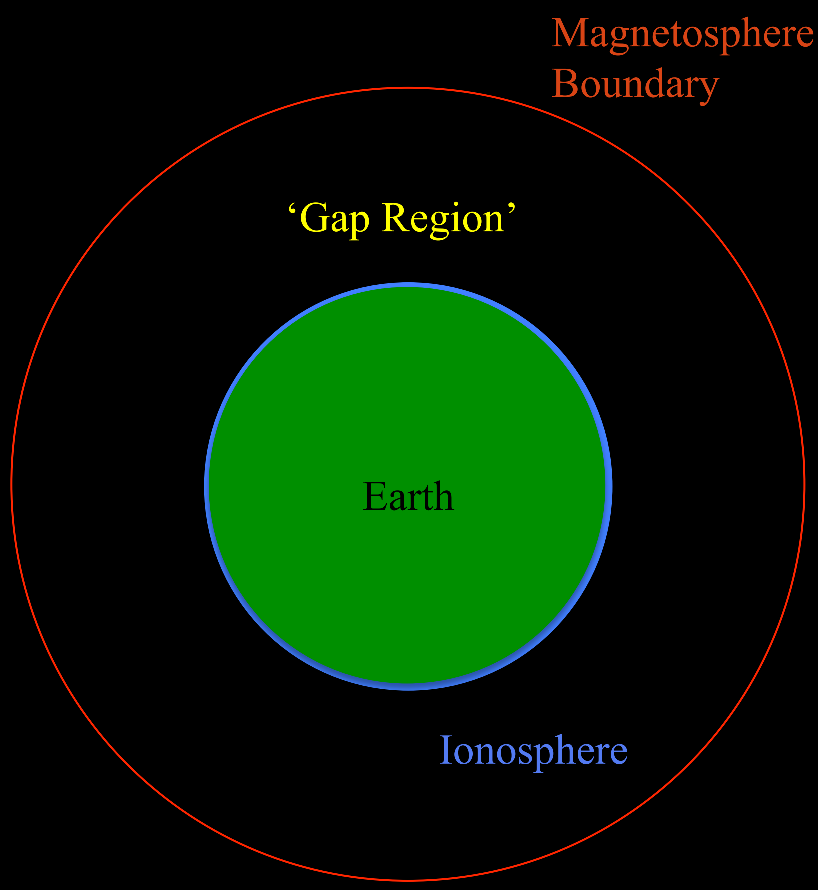


$$\nabla \bullet \left(\Sigma_P + \Sigma_H \right) \nabla \Phi = J_{\parallel} \sin(\eta)$$

- GCMs have three key components
  - MHD simulation of the magnetosphere
  - MI Coupling Module
  - Ionosphere-Thermosphere Model
- Electrical functions of the MI coupling module
  - Addresses part of the 'gap region'
  - Solves the conservation of current equation
  - $J_{\parallel}$ is determined from magnetospheric boundary
  - Computes auroral precipitation parameters
    - Flux and energy are determined from MHD density and temperature via empirical relationships
    - Uses Knight relationship to relate $J_{\parallel}$ to $\varepsilon_{\parallel}$
  - Pedersen and Hall conductances also include the effects of solar EUV radiation

Mass Coupling

- In most GCMs there is a 'gap region' between the ionosphere-thermosphere model and magnetosphere model
- Magnetosphere Boundary Conditions
  - LFM uses Hard wall boundary condition
    - No mass through inner boundary
    - $V_{\|}$ in reflected and $v_{\perp}$ from Electrical BC
  - For inflow need to specify
    - Location, location, location
    - $V_{\|}$, T, and density
    - Mass flux is useful, but I still need to specify fundamental MHD
- Ionosphere Boundary Conditions
  - TIE-GCM has a prescribed high altitude boundary condition
    - Outflow/Inflow on the dayside/night
    - Function of magnetic latitude



Review Paper

- Review paper published in Magnetotails in the Solar System
  - Contains details about equations and numerical methods
  - Unfortunately in AGU Monograph
    - doi:10.1002/9781118842324.ch22
    - Have PDF file if anyone wants a copy

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Review of global simulation studies of the effect of ionospheric outflow on the magnetosphere-ionosphere system dynamics.

M. Wiltberger[1]

Abstract. Since the detection of O^+ ions by satellites in the 1970s it has been known that the ionosphere is an important source of plasma in the Earths magnetotail. More recent observations have shown that these ions can become a dominant component of the plasma in the plasmasheet. Early work in substorm research considered a role for O^+ in the onset of plasma instabilities and their relationship to substorm onset. Theoretical analysis of reconnection in multi-fluid plasmas has shown that the presence of a heavy ion slows the reconnection rate raising interesting implications for the occurrence rate of substorms. Global scale simulations have been used to effectively model the interaction of the solar wind with the tightly coupled magnetosphere-ionosphere-thermosphere system. These models are now beginning to develop methods to include mass outflows from the ionosphere. Techniques for including these outflows include both empirical and first principle models. In the empirical techniques the relationship between observed parameters such as Poynting flux and outflow are used to specify both the location and intensity of the outflow coming from the cusp and auroral regions. First principle models of the polar wind typically use a large set of single flux tube simulations to describe the plasma flowing out over the entire polar cap. In both approaches significant impacts on the state of the magnetosphere are seen when the ionospheric plasma is included. These affects include improved agreement with D_{ST} observations, changes in the cross polar cap potential, and alteration of the length of the magnetotail. Furthermore, some simulation results have demonstrated a role for O^+ in the transition from steady magnetospheric convection into the sawtooth intervals containing multiple storage and release segments.

1. Introduction

Since the discovery of O^+ ions in the magnetosphere [*Shelley et al.*, 1972] it has been widely known that the ionosphere is an important source of magnetospheric plasma [*Sharp et al.*, 1985]. During active times observations have shown that O^+ can become a major component of the plasmasheet with O^+ to H^+ number density ratios approaching unity [*Peterson et al.*, 1981] and energy density ratios also approaching unity [*Nosé et al.*, 2000]. During superstorms *Nosé et al.* [2005] reported that the energy density ratios can become large as 10-30 more O^+ . *Kistler et al.* [2005] showed that these O^+ ions are a major contributor to the cross tail and ring current systems in the magnetotail. The detailed study of Akebono observations by *Cully et al.* [2003] found correlations between O^+ densities and solar wind conditions including; dynamic pressure, electric field, the magnitude of the interplanetary magnetic field (IMF), and the direction of the IMF.

While not the focus of this review, significant research efforts have investigated the many different pathways that ions follow in acquiring energy during their exodus from the ionosphere [*Yau and Andre*, 1997; *Schunk*, 2007, and references therein]. These processes produce two main categories of outflow. One is the classical polar wind, composed principally of light ions (H^+, He^+) that are accelerated upward by an ambipolar electric field supported by thermal pressure gradients. The second category, sometimes referred to as generalized polar wind, includes outflow driven by process other than those that create the classical polar wind. One pathway involves acceleration of ions in the direction perpendicular to the magnetic field, followed by mirror force lifting. This process acts first on heavy ions (O^+, N^+) due to their larger Lamour radii [*Lemaire and Scherer*, 1978; *Cladis*, 1986; *Demars et al.*, 1996; *Ganguli*, 1996]. Parallel acceleration processes associated with field aligned currents (FACs) [*Ganguli*, 1996] and centrifugal acceleration [*Cladis and Francis*, 1992] can lead to ion conics and beams which are also classified as part of the 'generalized polar wind.' An additional pathway relies on the interaction of photoelectrons with the ambipolar electric field in the sunlit hemisphere. This interaction provides additional acceleration to the outflowing ions [*Khazanov et al.*, 1997]. As *Yau et al.* [2007] point out, it can be challenging observationally to distinguish between the classical and generalized polar wind so we shall use the term polar wind to refer to outflow of ions, mainly H^+, He^+, and O^+, from the ionosphere into the magnetosphere. The outflow flux and energy of the polar wind depends on the density of the ionospheric source population and the downward flow of electromagnetic power and precipitating particles.

In this book, *Wing and Johnson* provide a comprehensive review of the pathways for entry and transport of solar wind ions into the magnetotail. The entry from the solar wind can involve double cusp reconnection, Kelvin-Helmholtz instability, or kinetic Alfven waves. Once in the magnetotail ExB and gradient curvature drifts play important role in plasma transport and the specific entropy becomes a important parameter for tracking the transport of the solar wind ions. The pathway ions of ionospheric origin take into the magnetosphere depends upon their primarily on their source region. Ions coming from the cusp subjected to transverse heating processes move up the field line as they are convected across the polar cap. As [*Horwitz*, 1986] and [*Chappell et al.*, 1987] describe the resulting velocity filter effect

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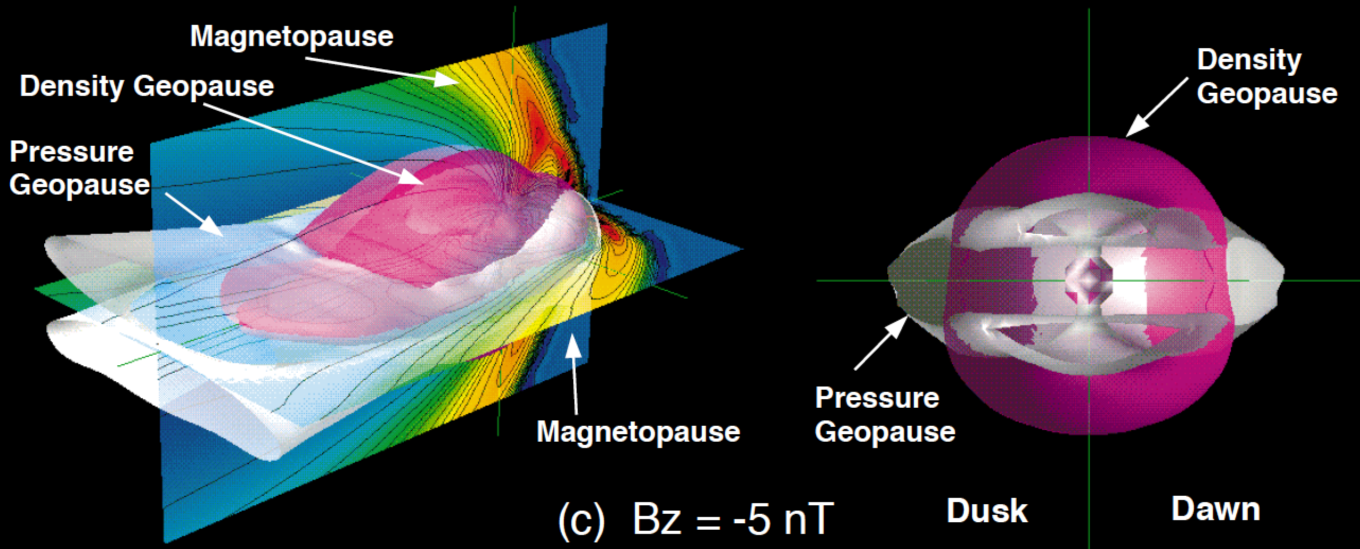
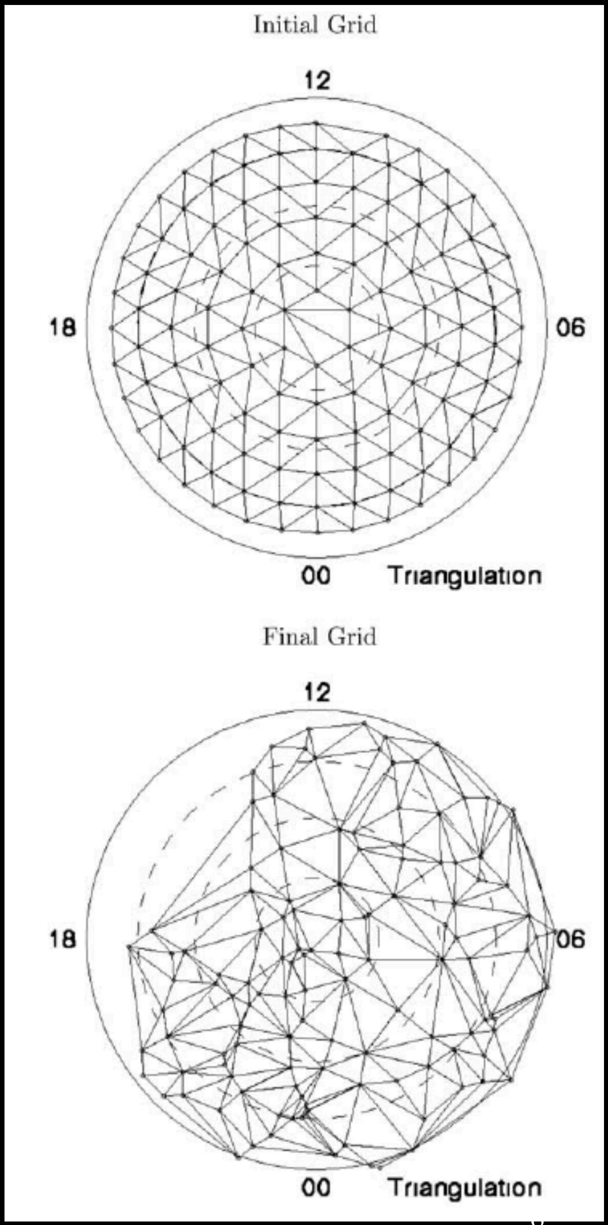
Winglee Outflow Method



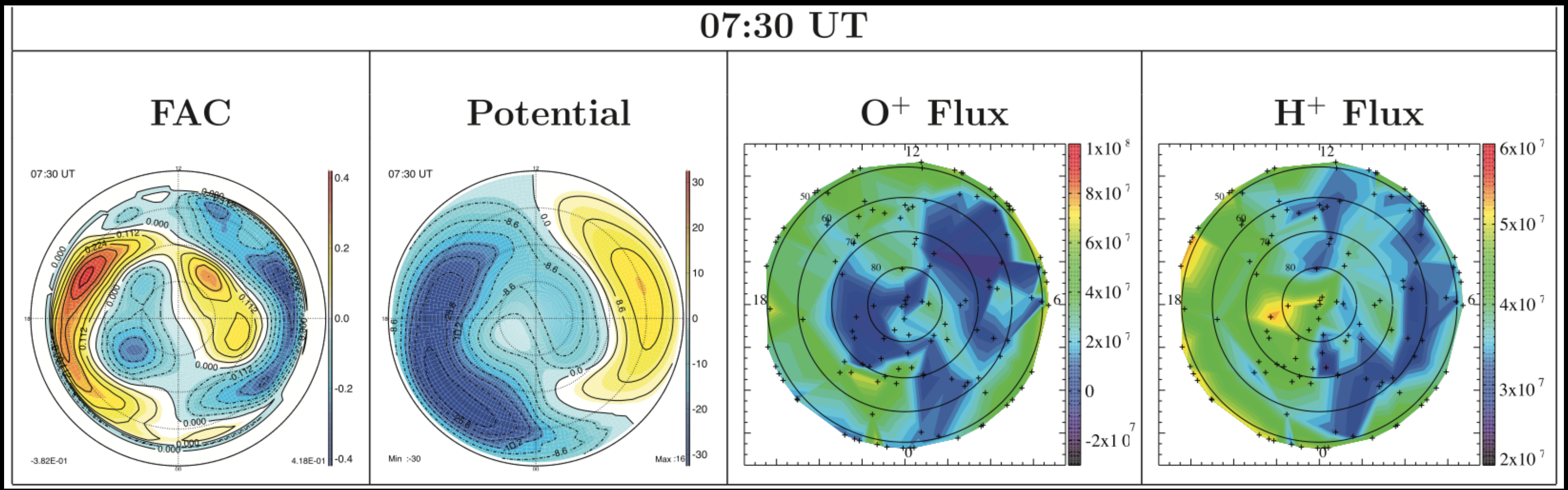
- Outflow method based upon centrifugal acceleration
  - Ion density at inner boundary held fixed
    - H^+ set to 400 cc with O^+ set a 5-100% H^+ density
  - Gravitational term increased to 30 m/s
  - Fluence $6x10^{26}$ to $2x10^{27}$ ion/s
- Identified the location of density and pressure geopauses in the simulation results

SWMF - Polar Wind Outflow Model

- *Glocer et al.* 2009 developed the PWOM as a part of the SWMF
  - Field-aligned, multi-fluid, multi-field line model
  - Coupled to multispecies-MHD magnetosphere and ionosphere electrodynamics model
- On a single field line it builds upon the work of *Gomobsi and Nagy*, 1989 to solve for transport of H^+, O^+, He^+, e^-
- Multiple independent field lines are then computed to provide a solution for outflow across the polar cap
  - Delaunay triangulation is used to interpolate between unstructured grid and magnetosphere inner boundary

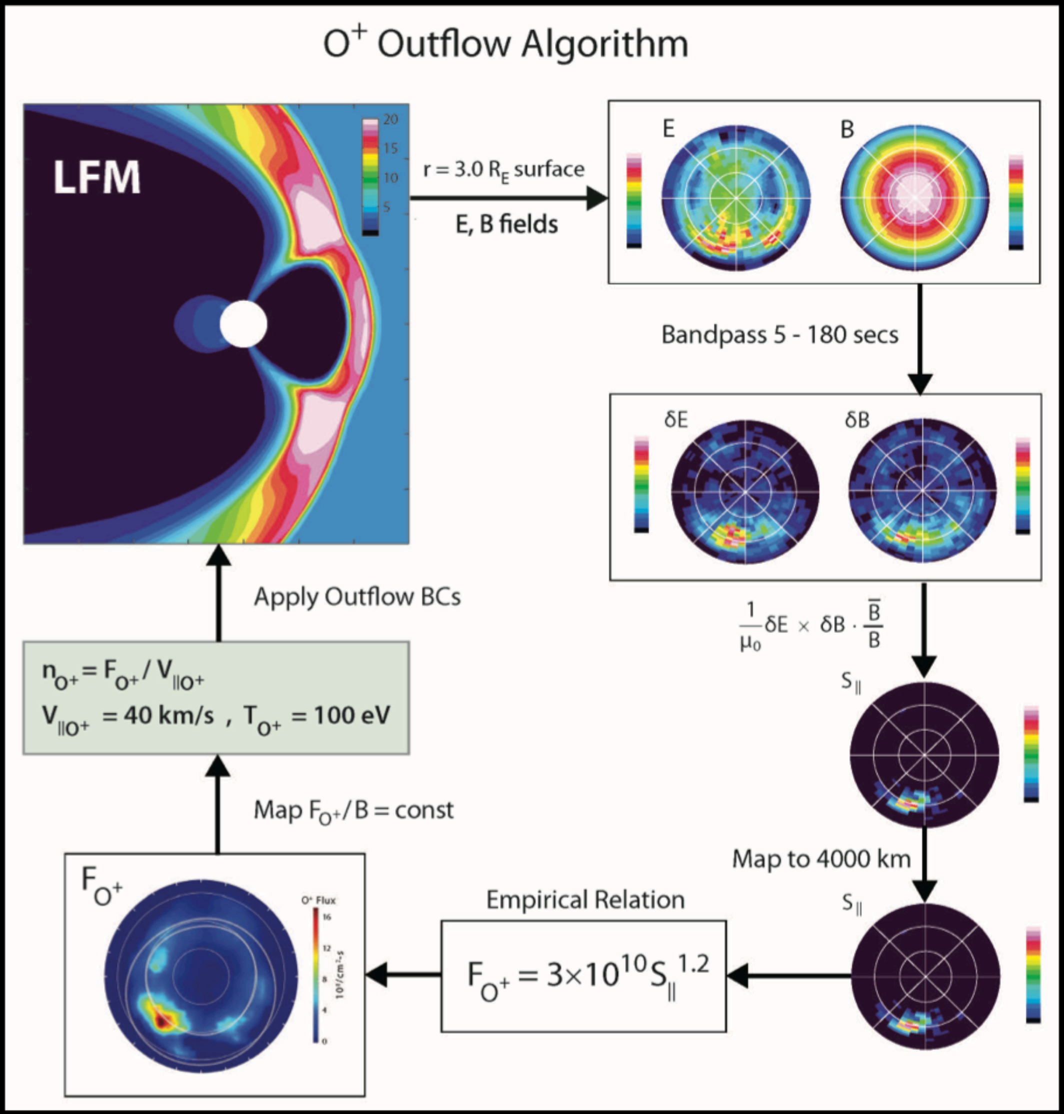


SWMF Outflow II



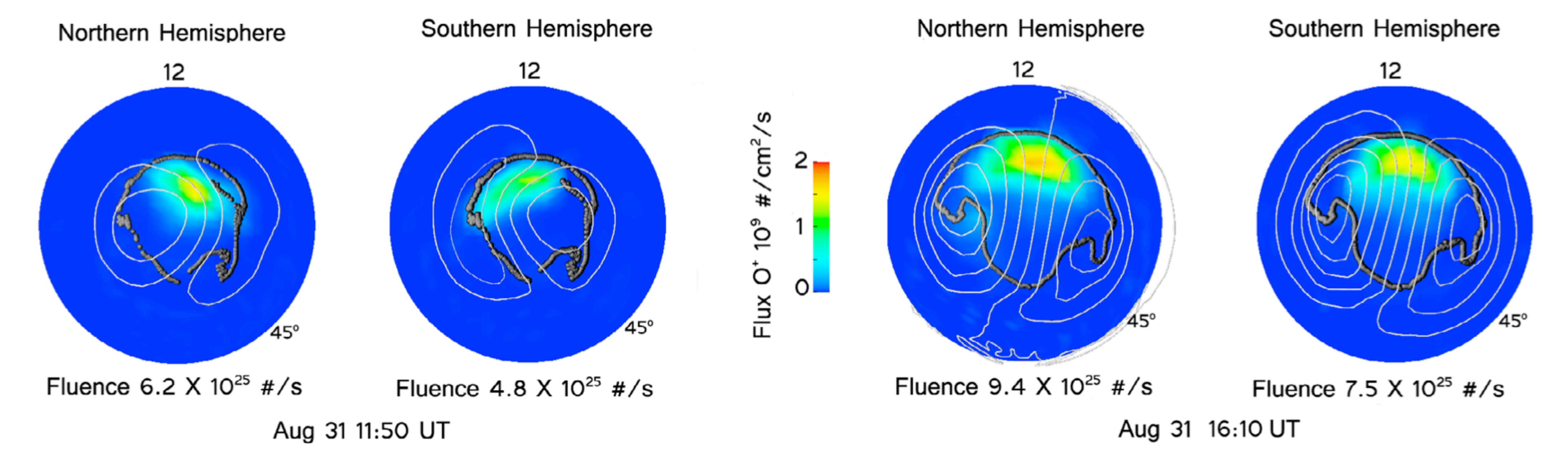
- PWOM Outflow pattern
  - Only O^+ has up/down flows at 1500 km altitude
  - O^+ outflows increase in regions of strong upward FAC
  - H^+ only upwards and less dynamic
- Other Outflow
  - Specified location – *Yu and Ridley, 2013*
    - Set values in auroral and cusp regions
  - Fixed Density BC
    - Situation similar to Winglee method and always occurring

MFLFM – Empirical Outflow



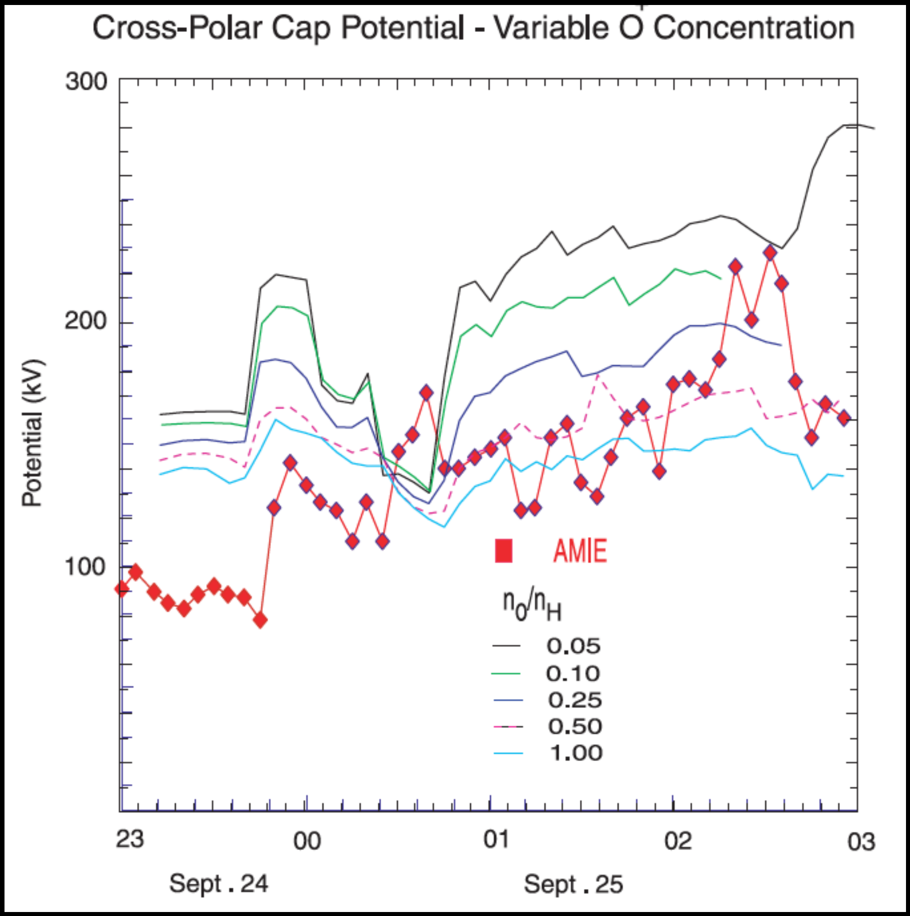
- *Brambles et al. 2010* presented results from the empirical outflow method
  - Based upon correlations between Poynting flux and Outflow reported by *Strangeway et al. 2005*
    - Both DC and AC have been used
  - Range of velocity and temperatures

MFLFM Outflow II



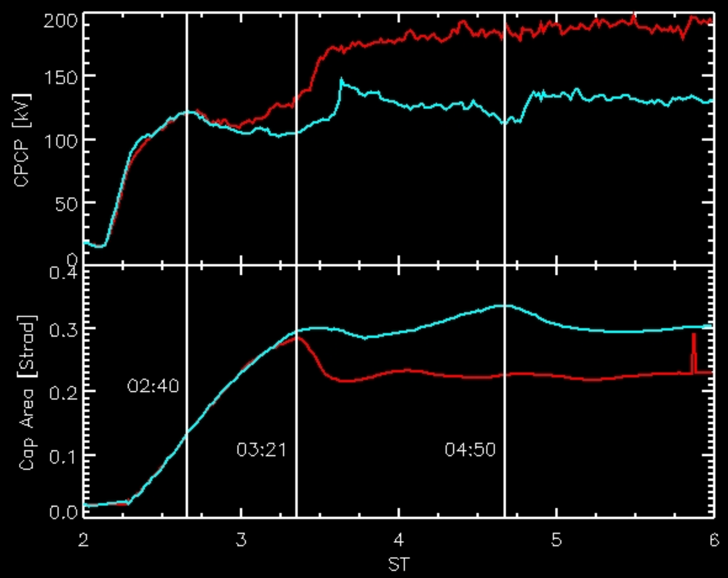
- Empirical Outflow pattern
  - O^+ coming mainly from cusp during CME passage
    - No significant flows from night-side aurora region
    - Clearly poleward of open/closed field line boundary
  - No H^+ or "classical" polar wind in this model
- Other Outflow
  - Specified location – *Wiltberger et al. 2010* and *Garcia et al. 2010*
    - Set values in auroral and cusp regions
  - Hard Wall Density BC
    - No Centrifugal Outflow as seen in the Winglee and SWMF
  - Ionosphere Polar Wind Model (IPWM)

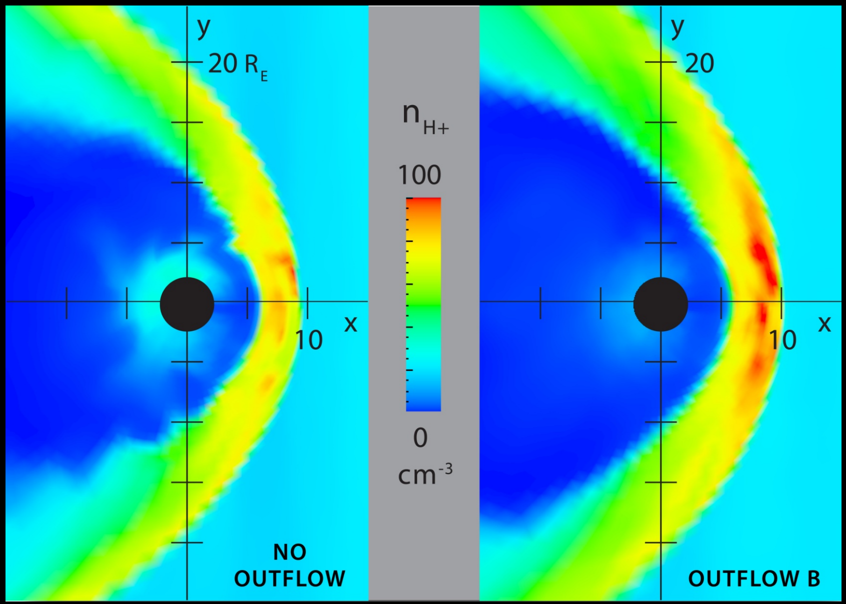
Convection Dynamics



- *Winglee et al. 2002* first reported seeing reduction in CPCP with outflow included
  - As ratio of O^+/H^+ is increased the magnitude of reduction increases
  - Approximately 70 kV reduction seen in case with strongest outflow
- Speculate that mass loading is the main reason for reduction
  - Increase in inertia in the inner magnetosphere caused by ions
  - Slower convection speed results in lower CPCP

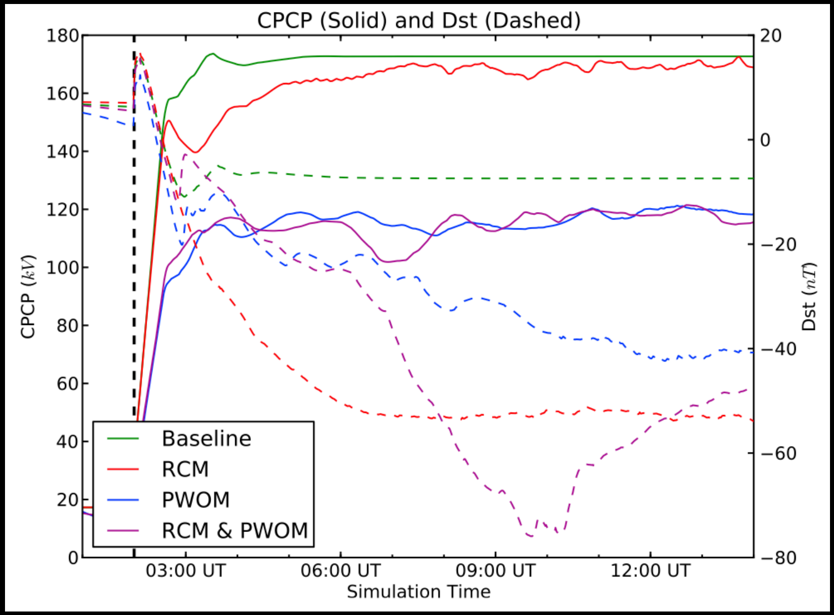
MFLFM CPCP Reductions

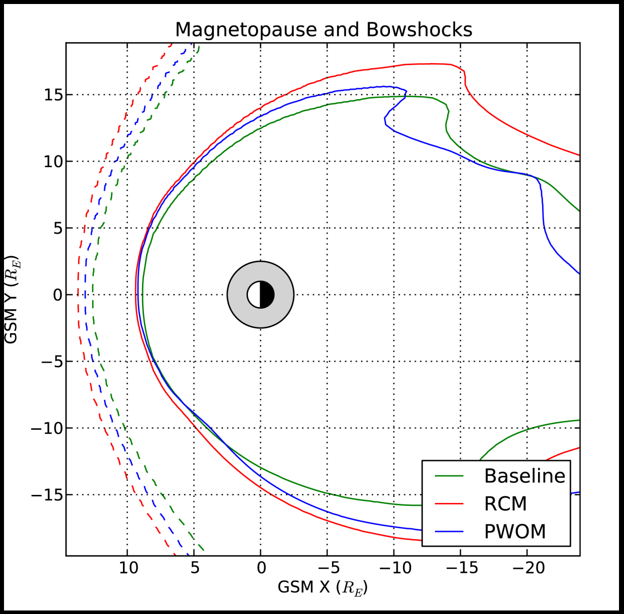




- *Wiltberger et al. 2010* saw reduction in CPCP for fixed cusp outflow
  - 50 kV reduction along with global reduction in R1 FAC observed
  - Believes “mass loading” affect is occurring
  - Other factors include changes in MI coupling via auroral precipitation model
- *Brambles et al. 2010* examined the magnetosphere inflation in more detail
  - Found up to 20% increase in stand off distance
  - Broader flow diversion region reduces flux to MP and thus lowers the CPCP
    - *Merkin et al. 2005 and Lopez et al. 2010* have more details about this mechanism

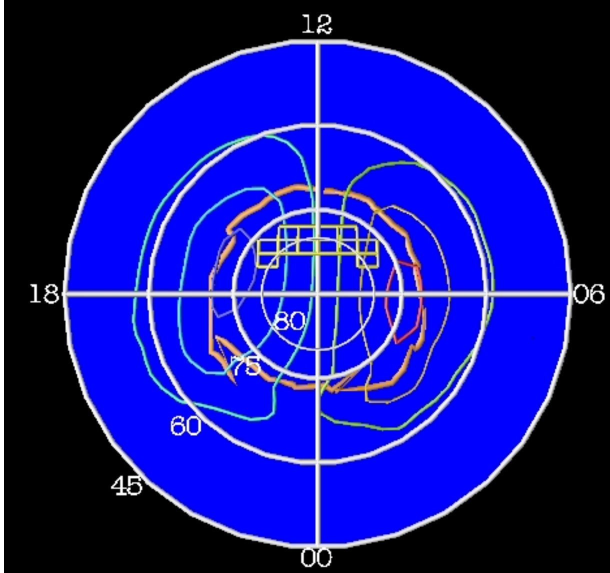
SWMF CPCP Reductions

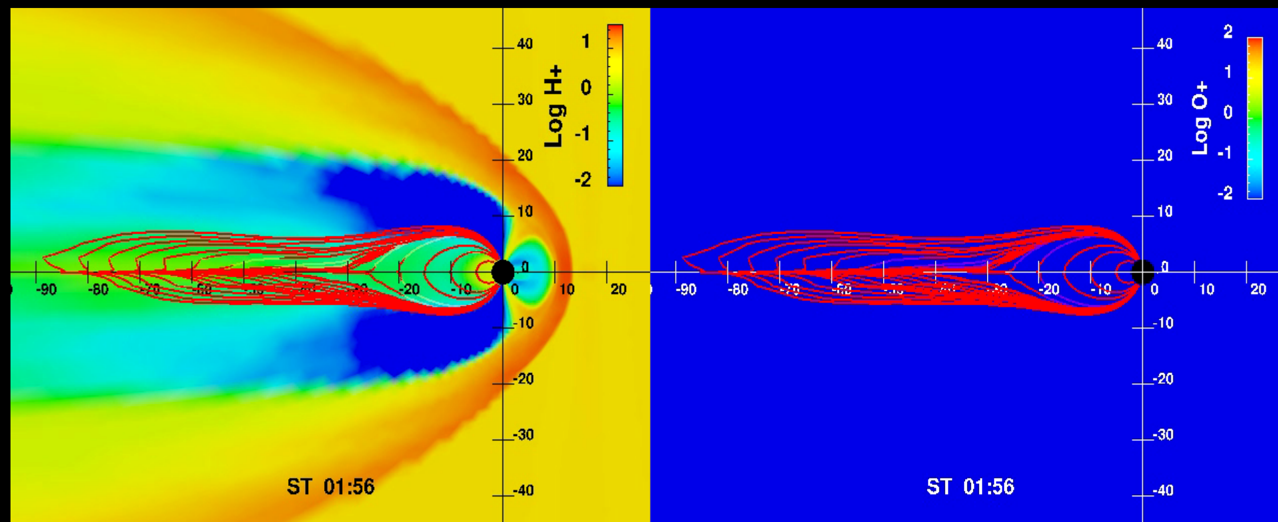




- *Welling and Zaharia 2012* examined conditions with SWMF using RCM and PWOM
  - RCM run has ~12 kV reduction and PWOM run has ~49 kV reduction in CPCP
- RCM run has largest inflation of MP with PWOM second
  - Authors concluded that inflation is not major cause of reduction
  - Speculate that mass loading and reduction of dayside reconnection rate are important

MFLFM - Cusp O^+ Outflow

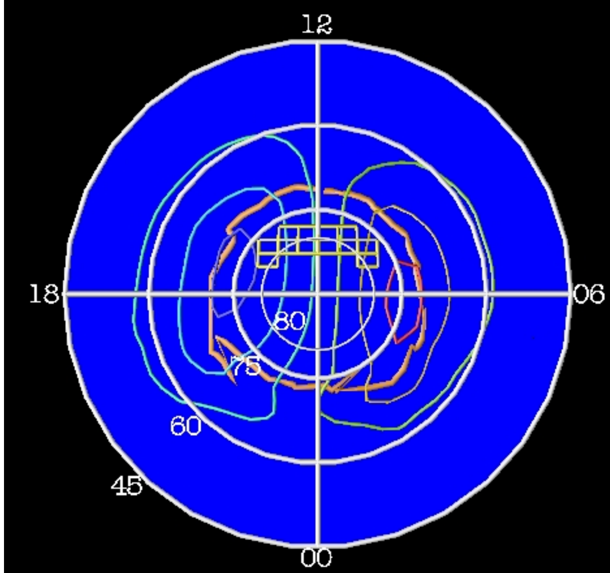


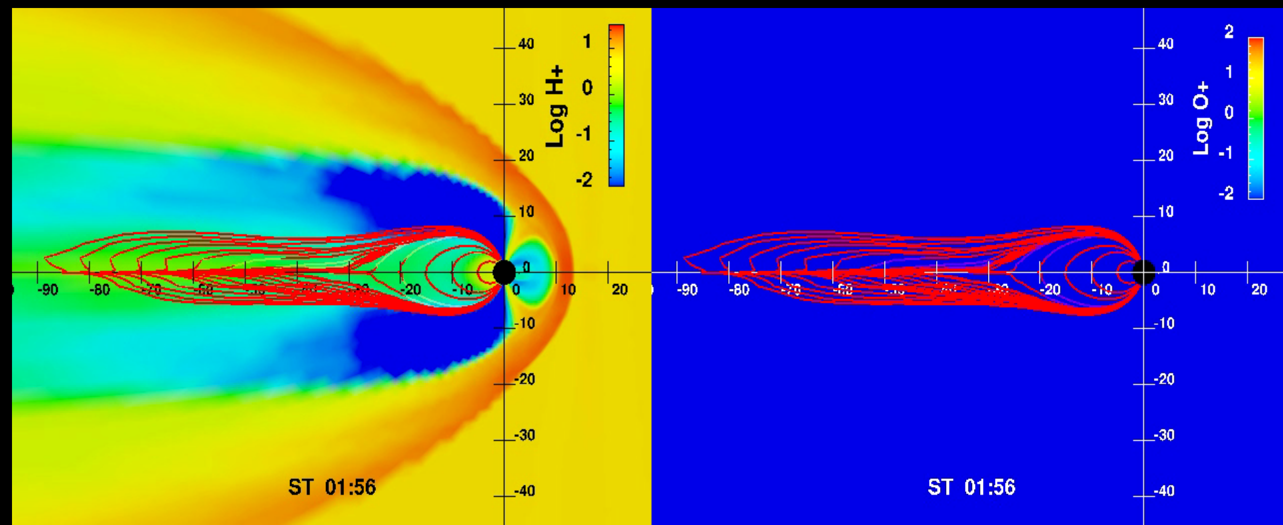


From *Wiltberger et al*. 2010

- We turn on O+ in cells whose ionospheric foot points map to a cusp region on the LFM ionospheric grid
  - Outflow from this region can lead to the onset of a second substorm in the simulation if the O+ interacts with the reconnection region in the mid-tail
  - If the flow is too fast or slow a second substorm does not occur
    - Case with outflow had velocity of 20 km/s and flux of 10^9 cm^{-2} s^{-1}

MFLFM - Cusp O^+ Outflow





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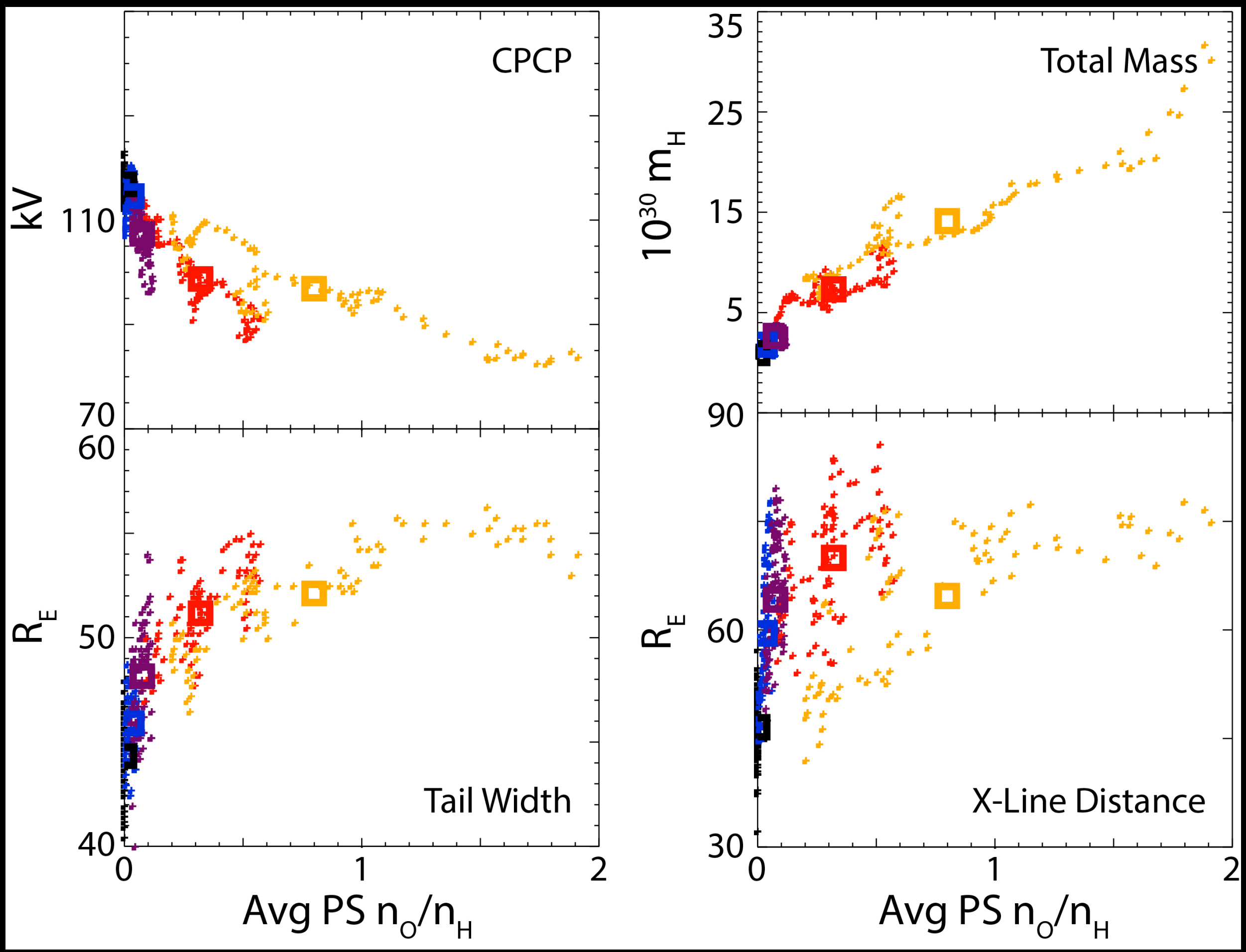
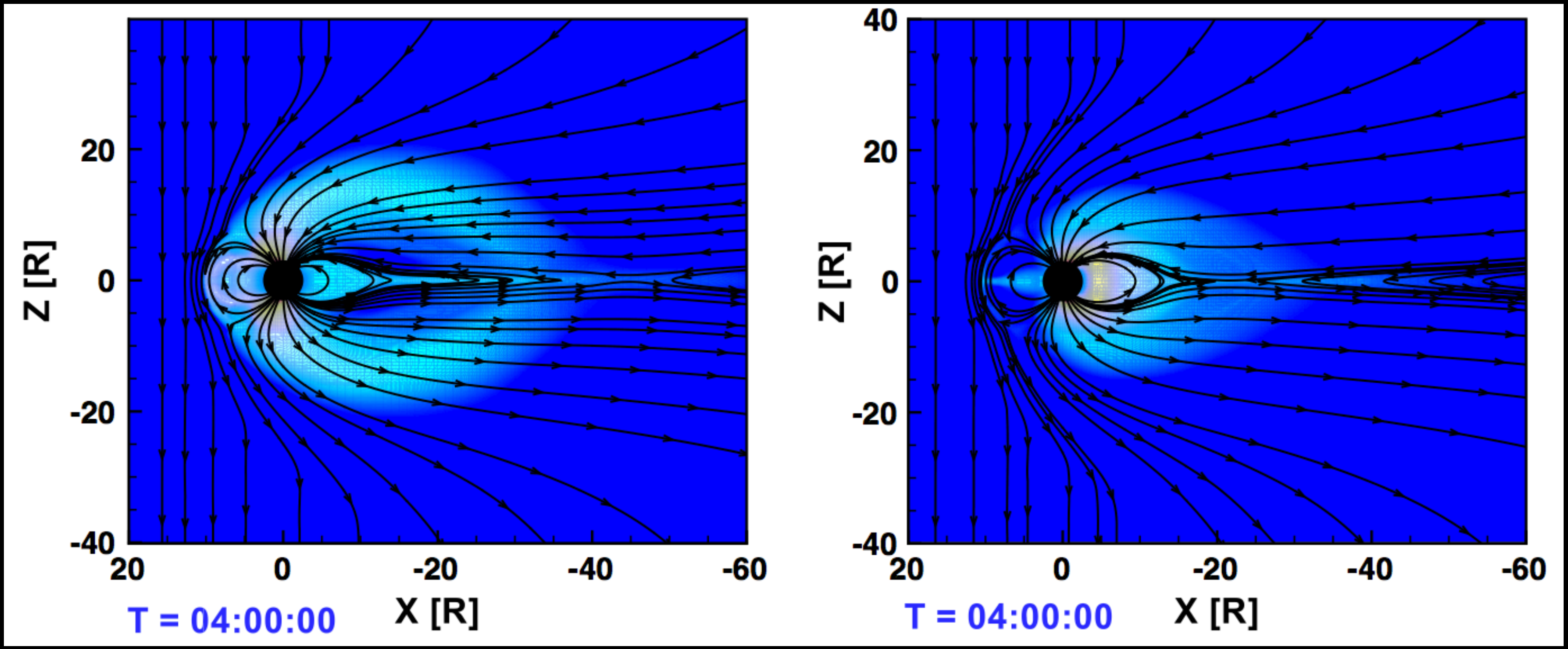
Night-side Auroral Outflow



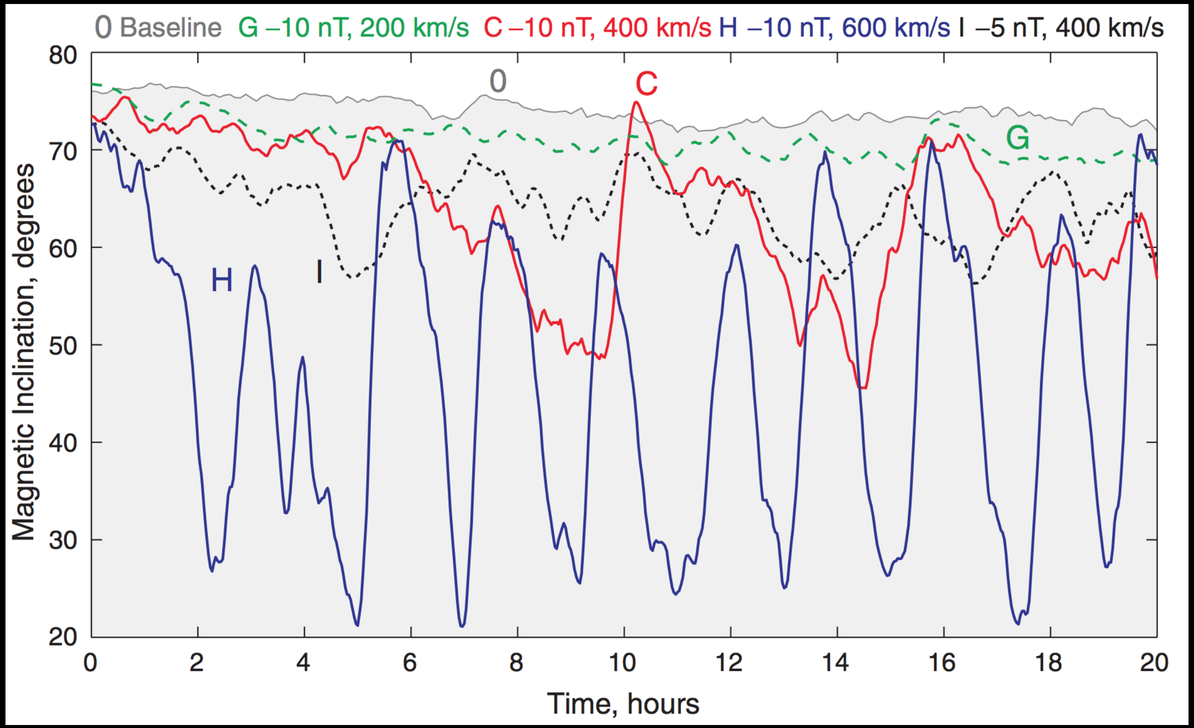
- *Garcia et al.*, 2010 examined the effects of outflow from the night-side auroral region use 4 different outflow cases
  - 40 km/s velocity
  - $4x10^7$ to $4x10^8$ cm^{-2} s^{-1} fluxes
- Results include
  - Increase flux reduces the cross polar cap potential
  - This outflow also tends to push the x-line further down the magnetotail
  - Increases the size of the magnetotail

SWMF – Cusp and Auroral Outflow



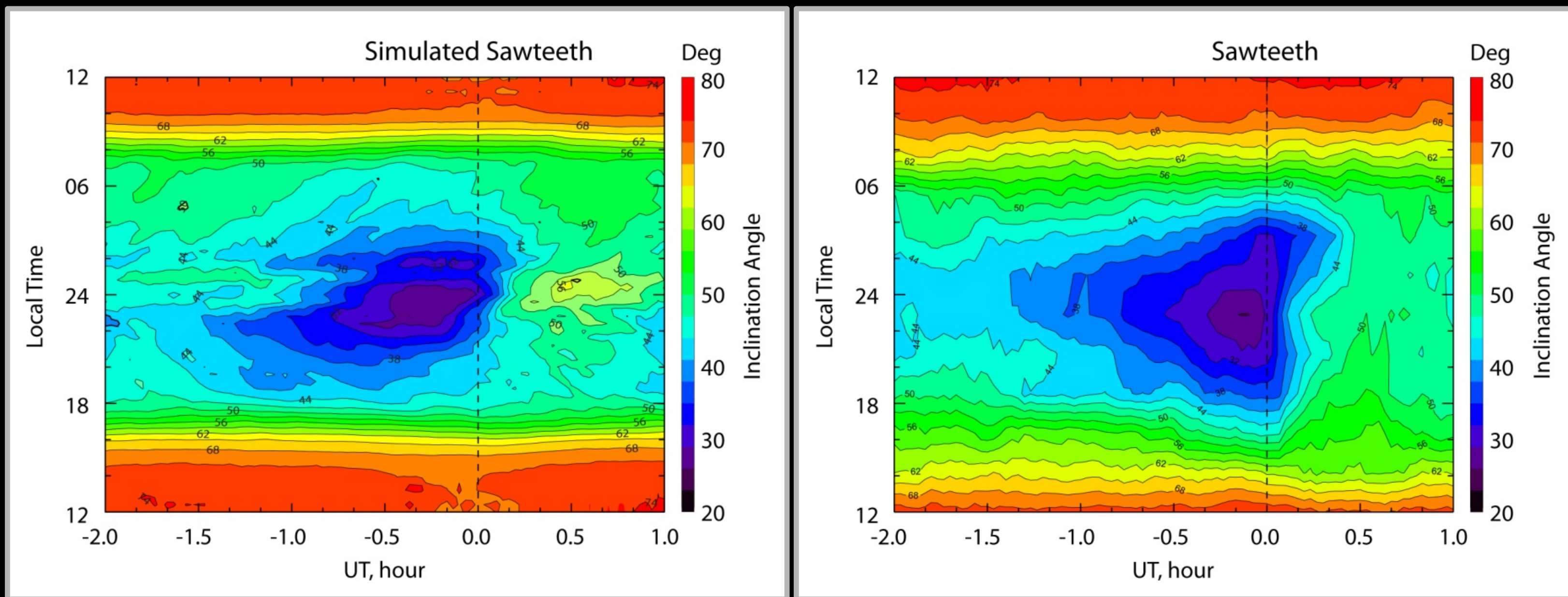
- Yu and Ridley, 2013 used SWMF with specified outflow coming from cusp and auroral zones
  - Conditions similar to Wiltberger et al. 2010 and Garcia et al. 2010
    - Velocity of 50 km/s and flux of $1x10^8$ cm^{-2} s^{-1}
- Examined impacts on magnetotail
  - New plasmoid seen in simulation with cusp outflow
    - Agree with *Wiltberger et al. 2010* conclusion that landing location important
  - Tail length increases with auroral flux intensity

MFLFM – Sawteeth Studies



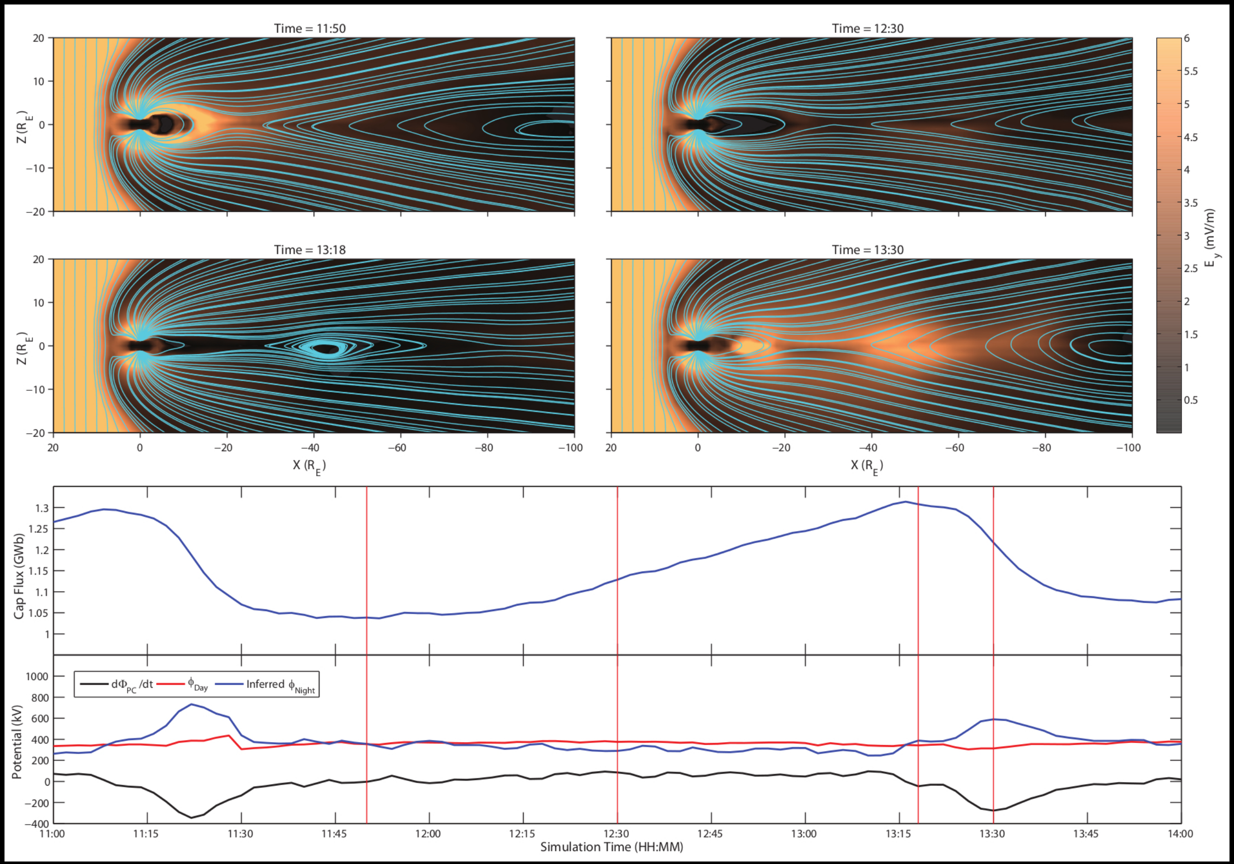
- *Brambles et al. 2011* Science paper used empirical model with idealized solar wind conditions
  - SMC state without outflow
  - Sawtooth events with O^+ outflow
    - Period depends on outflow intensity and strength of driving

MFLFM Sawteeth Global Structure



- Comparing the global structure in the MFLFM of geosync inclination angle with observations from *Cai and Clauer* 2009, shows consistent features both in local time extent and duration

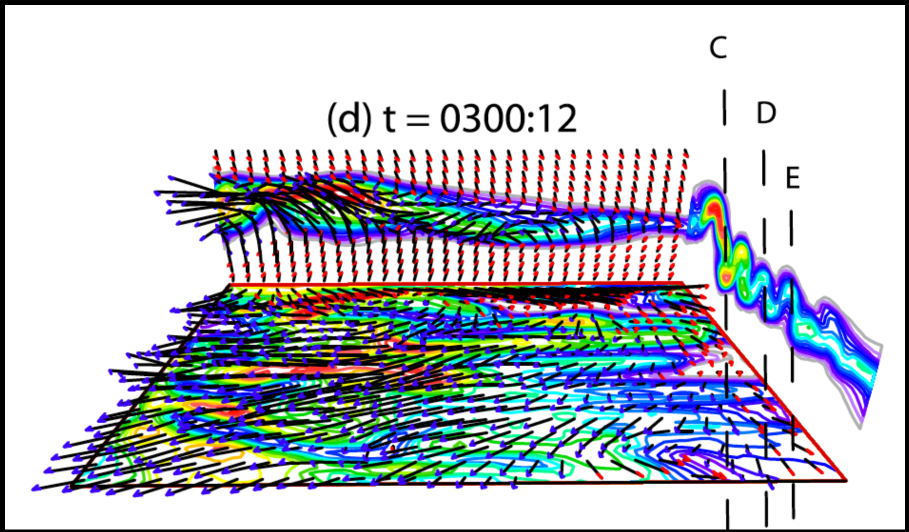
Properties of Outflow Driven Sawteeth

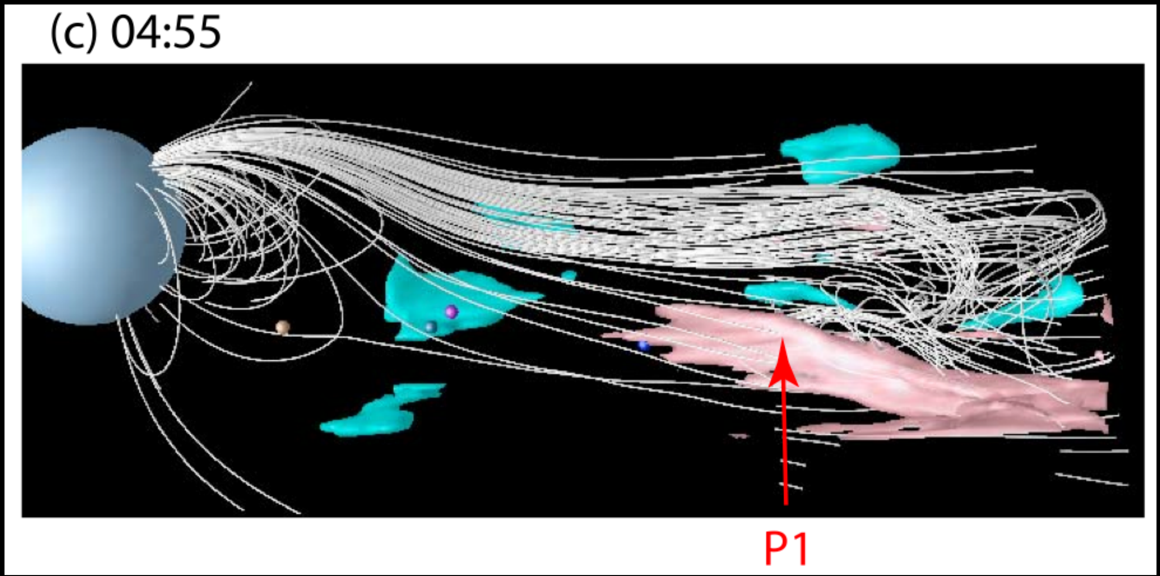


From *Ouellette et al.* 2013

- Careful examination of the sawtooth sequence shows
  - Outflow functions as feedback loop
    - O+ released during expansion phase drives next substorm
  - Nightside reconnection rate depends upon position of merging line
    - Tailward motion reduces inflow speed and B and disrupts balance with dayside

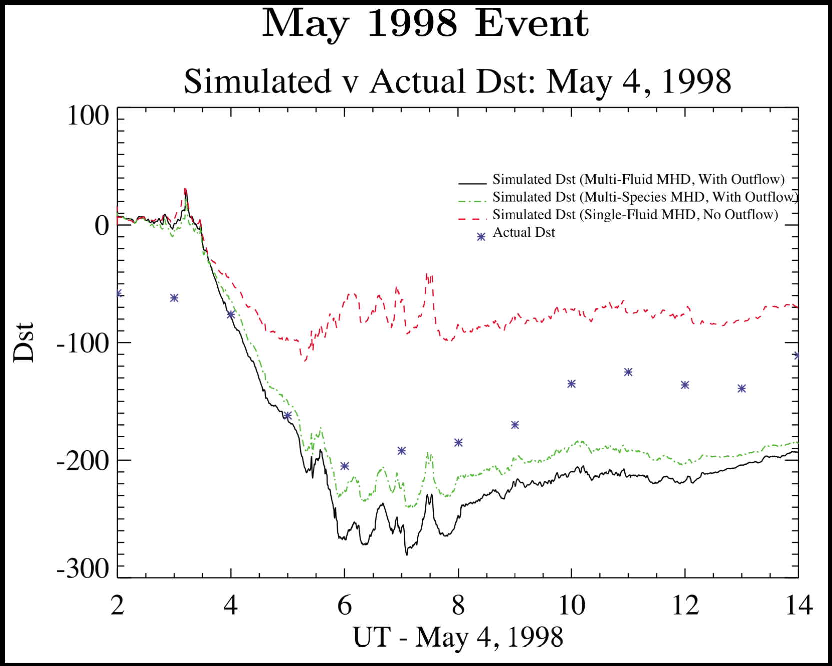
Winglee – O+ Impacts on Substorms

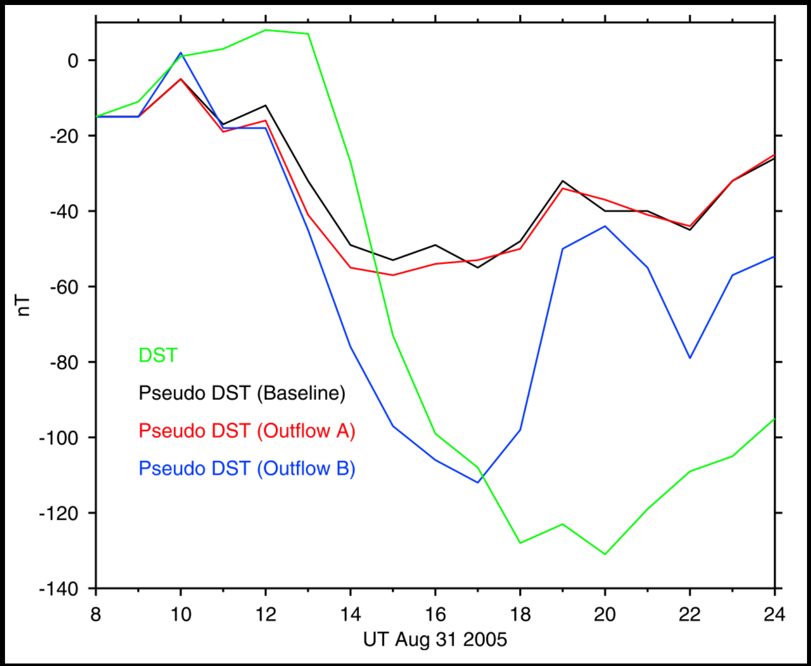




- *Winglee et al. 2009* and *Harnett et al. 2010* examined the role of O + ions on the substorm process
- Winglee studied idealized event
  - Found that O+ doesn't initiate substorm
  - O+ larger gyroradius allows for major role in injection and ring current
- Harnett studied 26 Feb 2008 THEMIS event
  - O+ ions arrive 10 min prior to onset
  - Conclude that substorm is internally triggered

MFLFM & SWMF – Ring Current

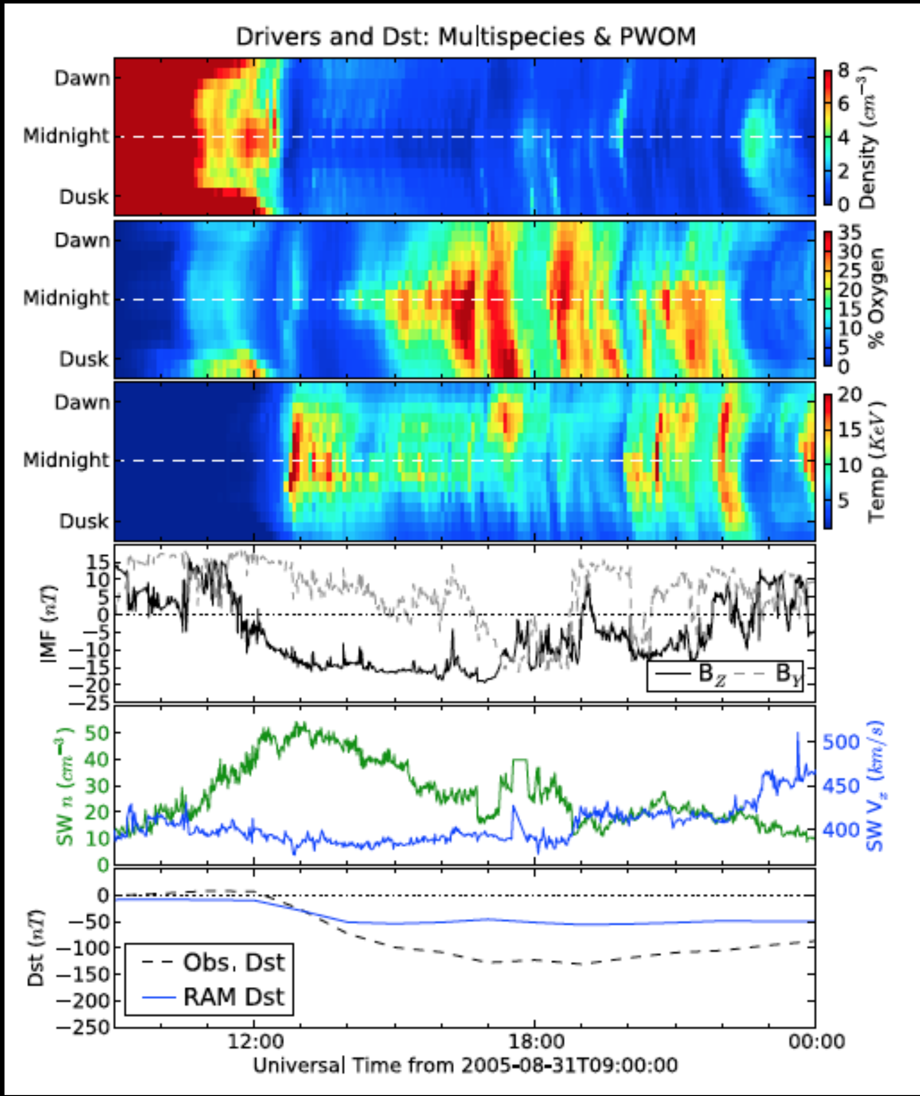




- Both the SWMF and and MFLFM see increases in ring current strength with O+ outflow included
  - *Glocer et al. 2009* actual sees slight over prediction, but major improvement with GOES magnetic field measurements
  - *Brambles et al. 2010* sees best agreement in simulation with strongest outflow

PWOM + RAM-SCB

- *Welling et al.* 2011 used a version of the SWMF with both PWOM and the RAM-SCB ring current model
- Including O+ outflow
  - Reduced the convection electric field
  - Lowered PS density and temperature
  - Increased complexity of ion distribution in PS



Conclusions

- All groups start from roughly same set of ideal multifluid MHD equations
  - Winglee group includes gravity
  - SWMF and MFLFM typical set electron pressure to fraction of ion pressure
- Outflow techniques is major source of differences
  - Winglee – Centrifugal only
  - SWMF – Centrifugal + PWOM or Location
  - MFLFM – No Centrifugal + Empirical or Location
- All groups report seeing reductions in CPCP
  - "Mass loading" major in Winglee suspected in others
  - MFLFM role for inflation and altering of MI coupling
  - SWMF minor role for inflation and change in reconnection
- Magnetotail dynamics
  - O^+ land location impacts multiple substorm dynamics
  - MFLFM reports role for O^+ in sawtooth events
  - SWMF and MFLFM both report increase in D_{st} with O^+ outflow

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